# Large Liquid Scintillator Detectors

## LENA (Low Energy Neutrino Astronomy)

Tobias Lachenmaier
Universität Tübingen

Fundamental Physics at
the Intensity Frontier
November 30 – December 2, 2011, Rockville

# LENA Design

**Cavern**

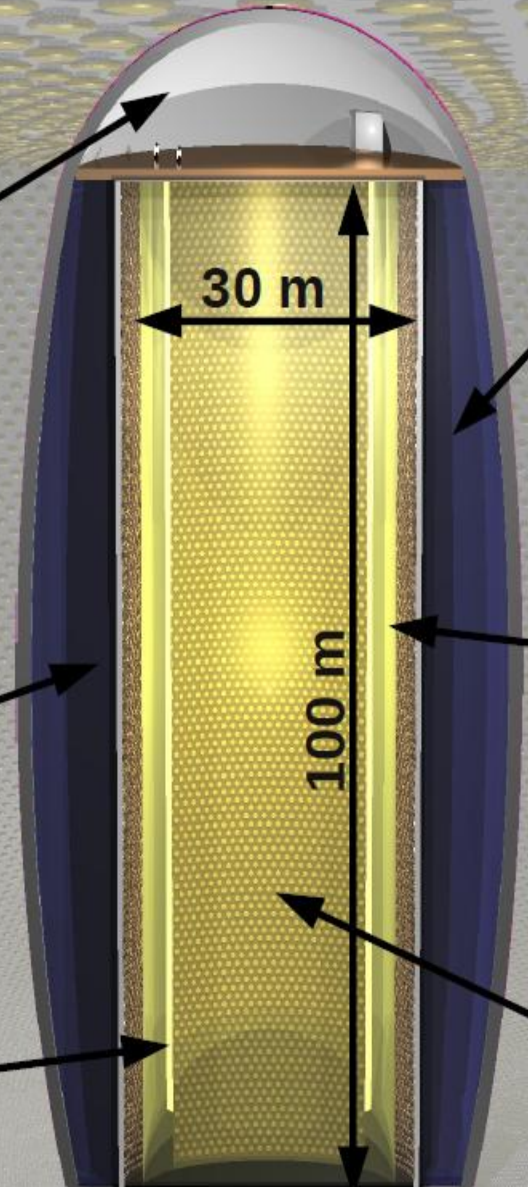
Height 115 m
Diameter 50 m

- Shielding of cosmic rays with 4000 m.w.e.
- Egg-shaped for increased stability

**Muon Veto**

- plastic scintillator panels on top
- 100 kt Water Cerenkov Detector with 5,000 8'' PMTs

→ fast neutron background reduction




**Steel Tank**

Height 100 m
Diameter 30 m

~65,000 PMTs (8“) with Winston Cones (1.75 x)

**Buffer Volume**

Thickness 2m
Non-scint. organic liquid shielding external radioactivity

**Nylon Vessel**

between buffer and target volume

**Target Volume**

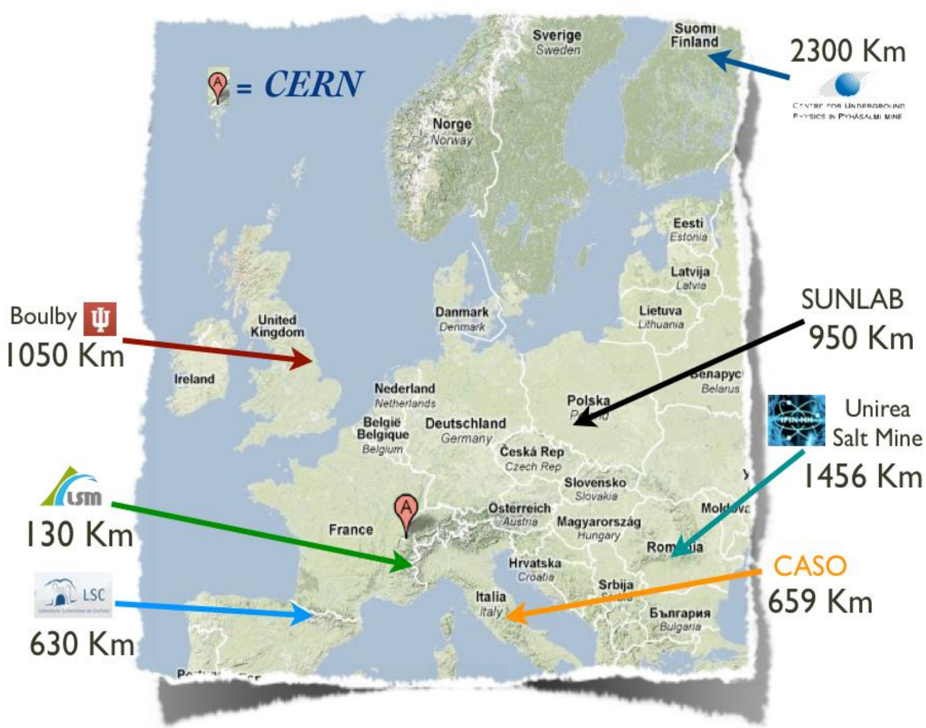
Height 100 m
Diameter 26 m

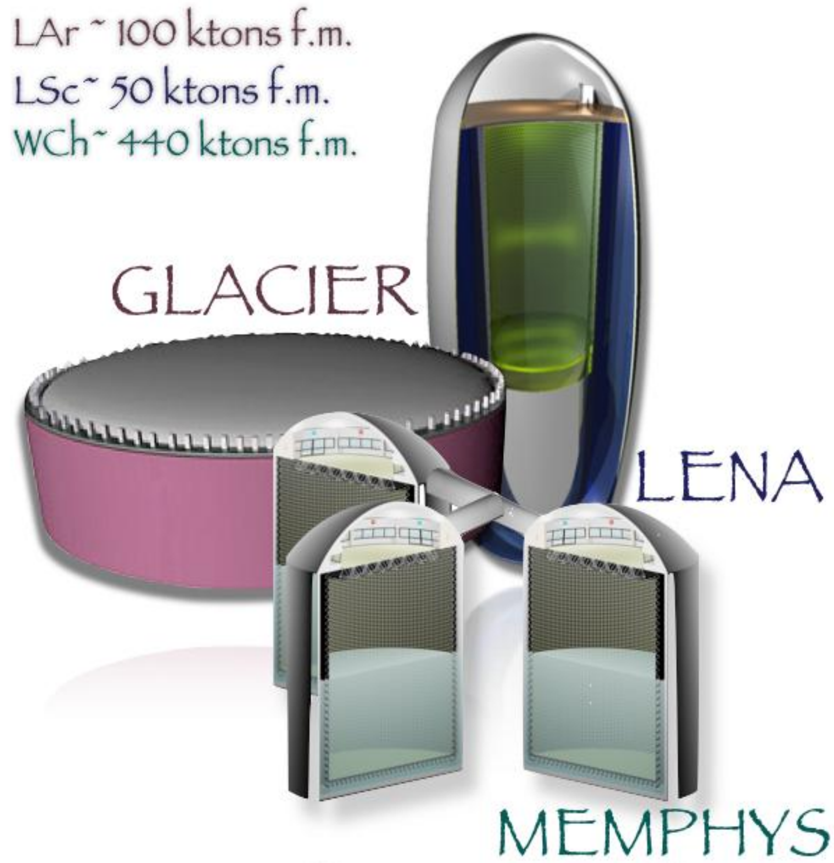
50 kt of organic liquid scintillator

# LAGUNA → LAGUNA-LBNO

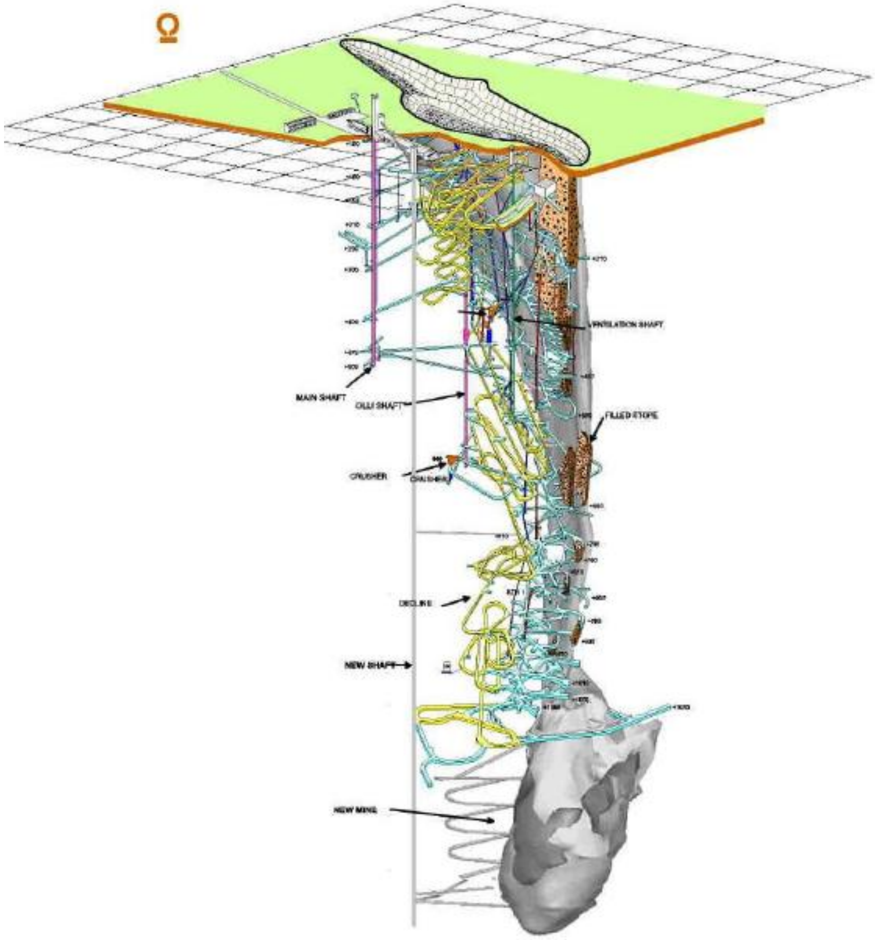
- Consortium of European science institutions and industry partners
- Design studies funded by the European Community (FP7)
- **LAGUNA:** detector site, cavern, and oscillation baselines (2008-11)
- **LAGUNA-LBNO:** detector tank, instrumentation, and beam source (2011-14)

***Seven sites, three detector technologies***



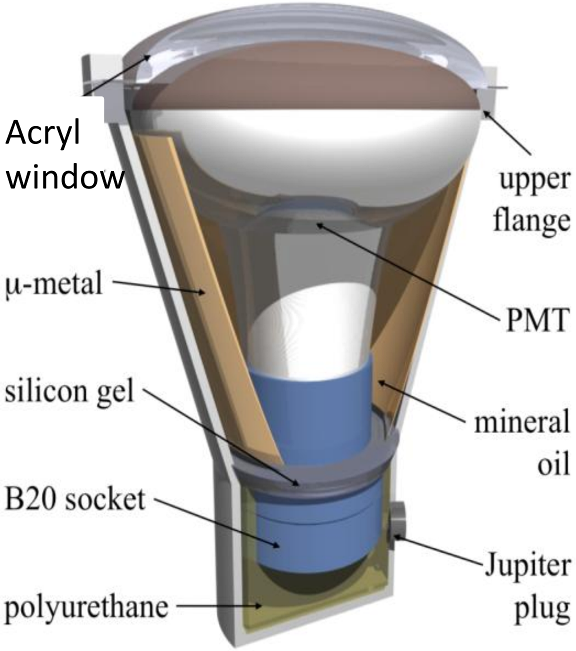
# Pre-feasibility study (within LAGUNA)




study for **a LENA detector at Pyhäsalmi**

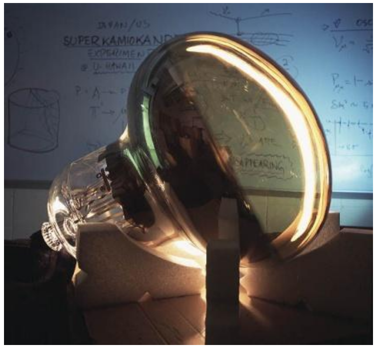
- depth of 1400-1500 m possible
- geological study completed
- vertical detector position
- infrastructure (ventilation, electricity, etc.) considered
- construction time of cavern ~ 4 yrs
- first cost and time estimate for the whole project

# Photo sensors/requirements




Pressure resistant encapsulation design (p > 15 bar) ready

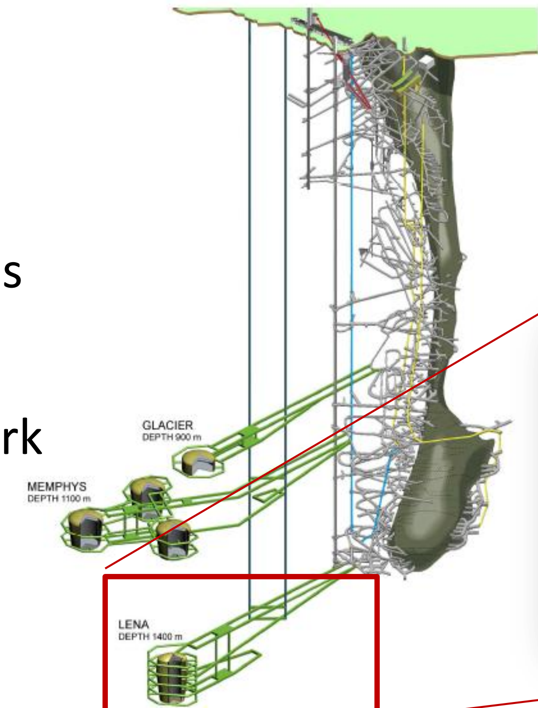
- Area Inner Detector: 10430 m²
  Targeted optical coverage: 30%
  → 3130 m² effective photosensitive area
- PMTs *probably* the only photosensor type
  - Durable for at least 30 years AND
  - Utilizable until start of construction

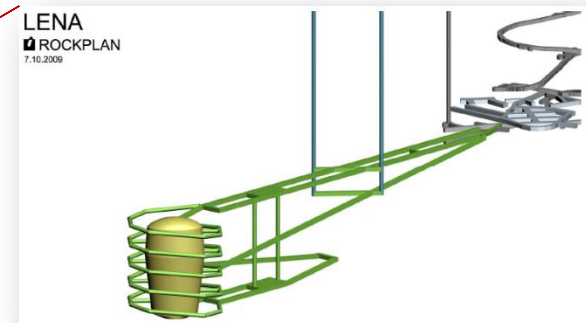


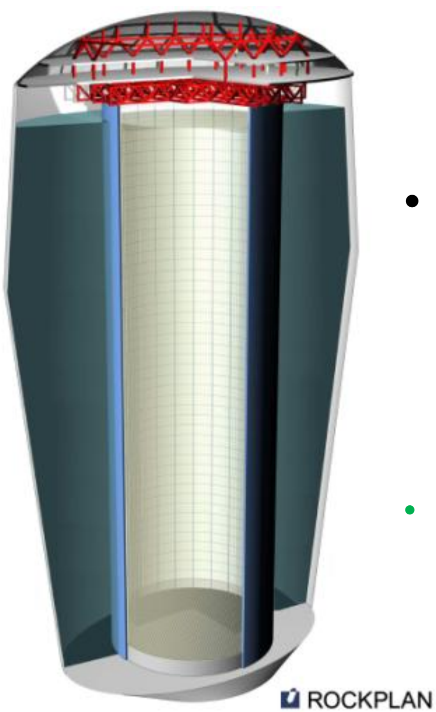

Important properties:
Transit time spread, afterpulsing, gain, dynamic range, area, quantum efficiency, dark noise, peak-to-valley-ratio, early + pre-pulsing, late pulsing, pressure resistance, long term stability, low radioactivity, price

# Cavern/tank construction

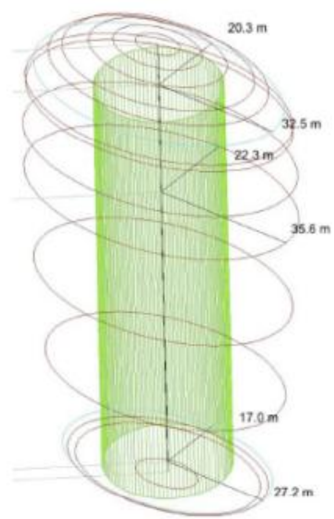
- tank + excavation study for Pyhäsalmi, Finland
- Based on existing study → substantial improvements
- Worked out excavation process and extra structures to fulfill safety requirements:
- 2 access tunnels, spherical work tunnel, 1 or 2 new shafts

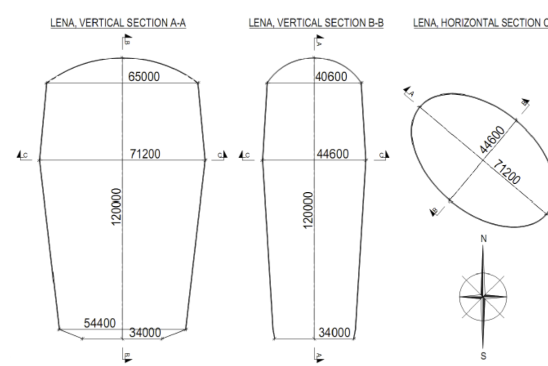



- Long term rock stability simulations → elliptical horizontal cross-section and kink in vertical cross-section
- → Larger volume for Water Cherenkov detector



# Detector construction: tank design

**Conventional Steel Tank**

+ well known, straightforward to build, robust

- expensive, single passive layer defense

**Sandwich Steel Tank**

+ cost effective, room for cooling, fast install, laser welds

- a lot of welding, little used solution, mechanically challenging

**Sandwich Concrete Tank**

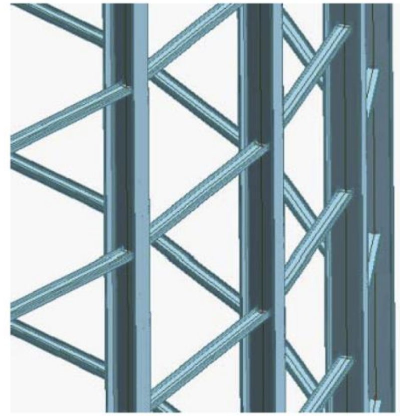
+ well known, straightforward to build, robust

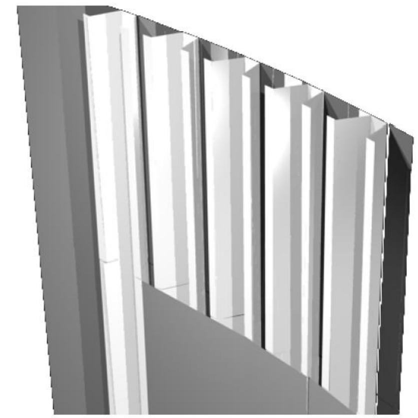
- steel plates and rebar prevent continuous casting, slow to build

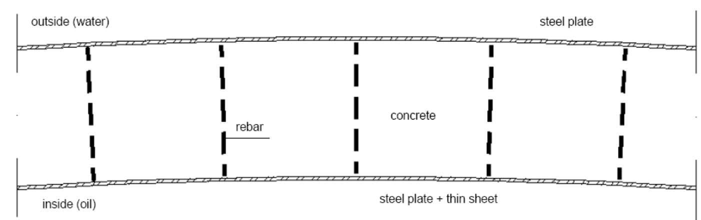
**Hollow Core Concrete Tank**

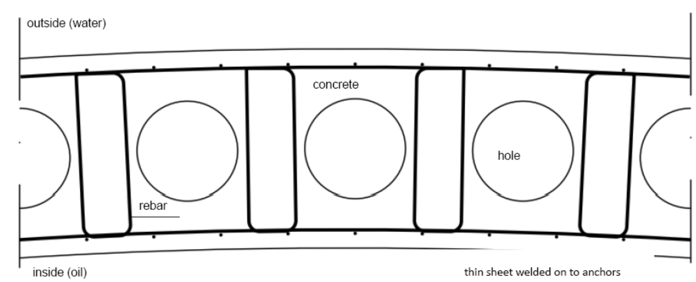
+ room for cooling, mechanically strongest

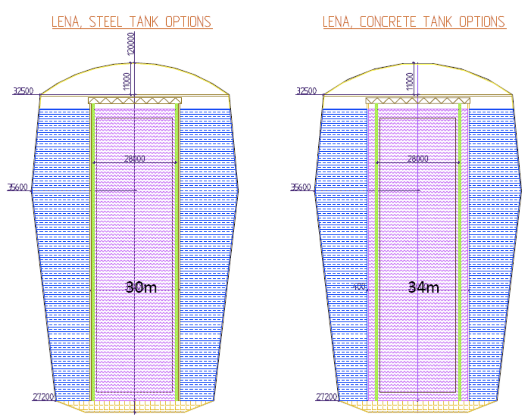
- little used solution, not very much experience








**LIQUIDS: Steel Tank**

Liquid scintillator oil
(51,000 m³, 43.8 kton)

Non-scintillating oil
(19,700 m³, 17.0 kton)

**TOTAL: 70,700 m³**

**LIQUIDS: Concrete Tank**

Liquid scintillator oil
(51,000 m³, 43.8 kton)

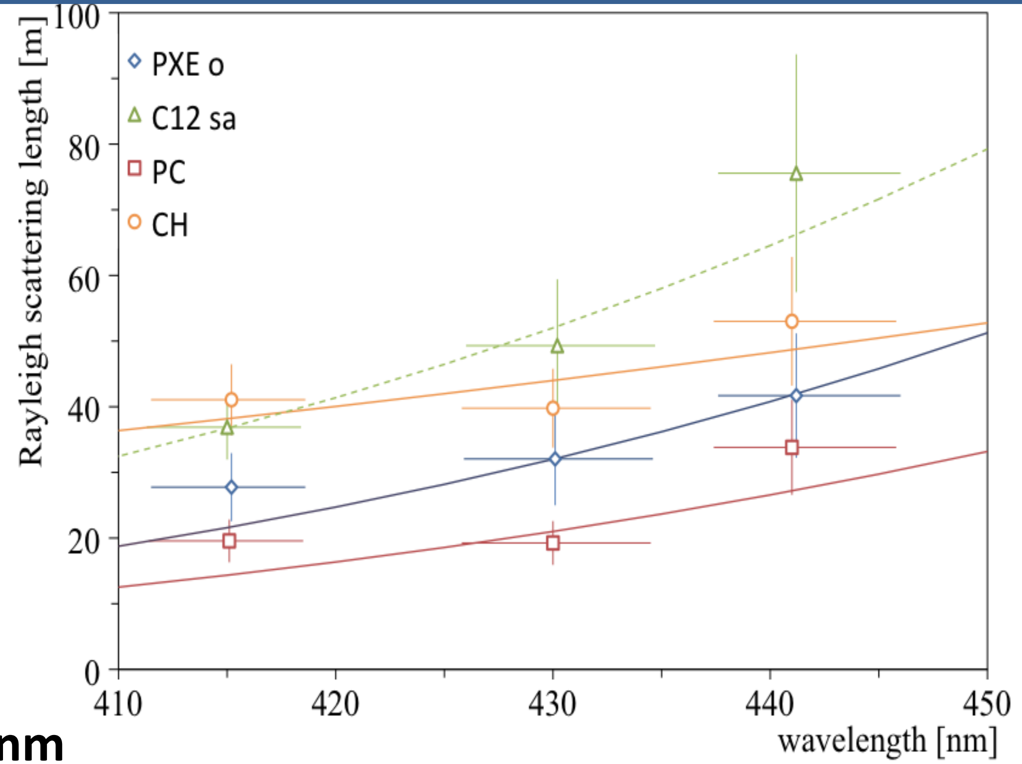
Non-scintillating oil
(39,800 m³, 34.2 kton)

**TOTAL: 90,800 m³**

M. Tippmann

# Optical properties: scattering length

- isotropic and anisotropic contributions measured
- anisotropic scattering in good agreement with Rayleigh expectation
- correct wavelength-dependence found
- literature values for PC, cyclohexane correctly reproduced




**Results for λ=430nm**

| Sample | $\ell_{is}$ [m] | $\ell_{an}$ [m] | $\ell_S$ [m] | $\chi^2$/ndf | $\ell_{ray}$ |
|---|---|---|---|---|---|
| PXE U | 22.8±1.0 | 33.6±4.0 | 13.6±0.7±1.0 | 1.39 | 32 |
| C12 SA | 258±54 | 40.9±3.9 | 35.3±3.0±2.2 | 0.92 | 37 |
| C12 AC | 132±16 | 48.5±5.6 | 35.4±3.1±2.3 | 0.77 | 37 |
| LAB P500 | 75.3±5.3 | 40.2±4.4 | 26.2±1.9±1.6 | 1.23 | 45 |
| LAB P550 | 60.5±3.7 | 40.5±5.2 | 24.3±1.9±1.5 | 1.29 | 45 |
| LAB 550Q | 66.3±5.7 | 40.0±4.6 | 25.0±1.9±1.6 | 0.80 | 45 |
| CH | n.a | 45.0±4.5 | 44.9±4.5±2.9 | 0.74 | 44 |

LAB (plus CH or C12) is fulfilling the requirements

*Michael Wurm*

# Scintillator and photosensors

Properties investigated

- Light yield
- Attenuation length
- Scattering length
- Refraction index
- Gamma Quenching
- Proton Quenching
- Fluorescence Decay Constants
- Scintillation Spectra

→ input for LENA MC to investigate physics potential

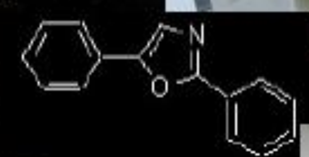
PMT testing in Garching and Borexino test stand @LNGS

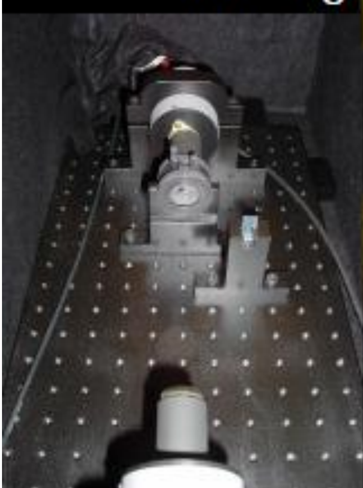
→ characteristics of possible PMTs

- afterpulses
- time jitter...

- collaboration with

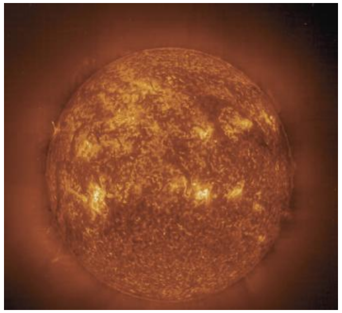
- MEMPHYS (PMm2), KM3Net
- INFN Milano, LNGS, Tübingen
- ETEL, Hamamatsu

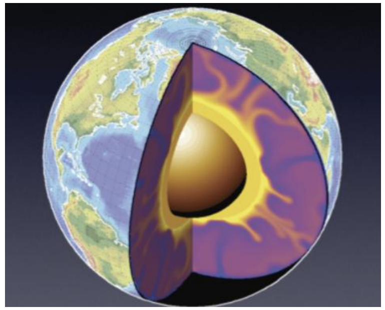


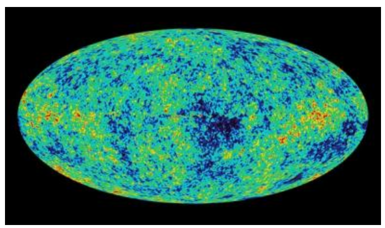


**Preselected mixture:**

**LAB + PPO**



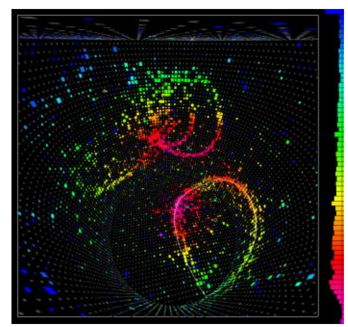


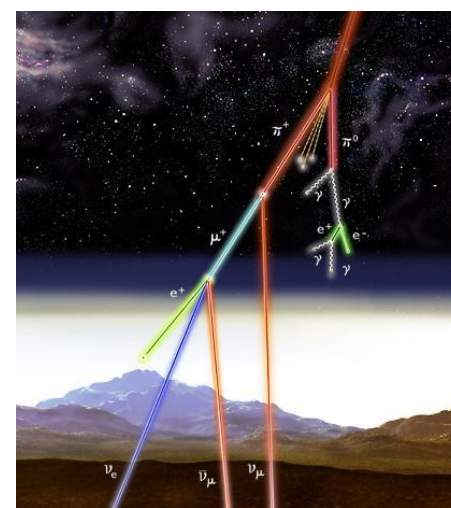
# Low Energy Physics

- Neutrinos from galactic Supernovae
- Diffuse Supernova neutrinos
- Solar neutrinos
- Geoneutrinos
- Reactor neutrinos
- Neutrino oscillometry
- Indirect dark matter search

# Physics in the GeV energy range

- Proton decay search
- Long baseline neutrino beams
- Atmospheric neutrinos





# A galactic SN in LENA

Possible reactions in liquid scintillator

- $\overline{\nu}_e + p \to n + e^+$
- $\overline{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$
- $\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$
- $\nu_x + {}^{12}\mathrm{C} \to {}^{12}\mathrm{C}^* + \nu_x$
- $\nu_x + e^- \to \nu_x + e^-$
- $\nu_x + p \to \nu_x + p$

**ca 15.000 events for a galactic SN**

**high statistics**
**energy dispersive**
**flavour resolving**
**time dispersive**

- electron anti-ν spectrum with high precision
- Electron ν flux with ~ 10 % precision
- Total flux via neutral current reactions
- Separation of SN models
- independent from (collective) oscillations in NC reactions

# Diffuse Supernova Neutrino Background

**Detection via Inverse Beta Decay**

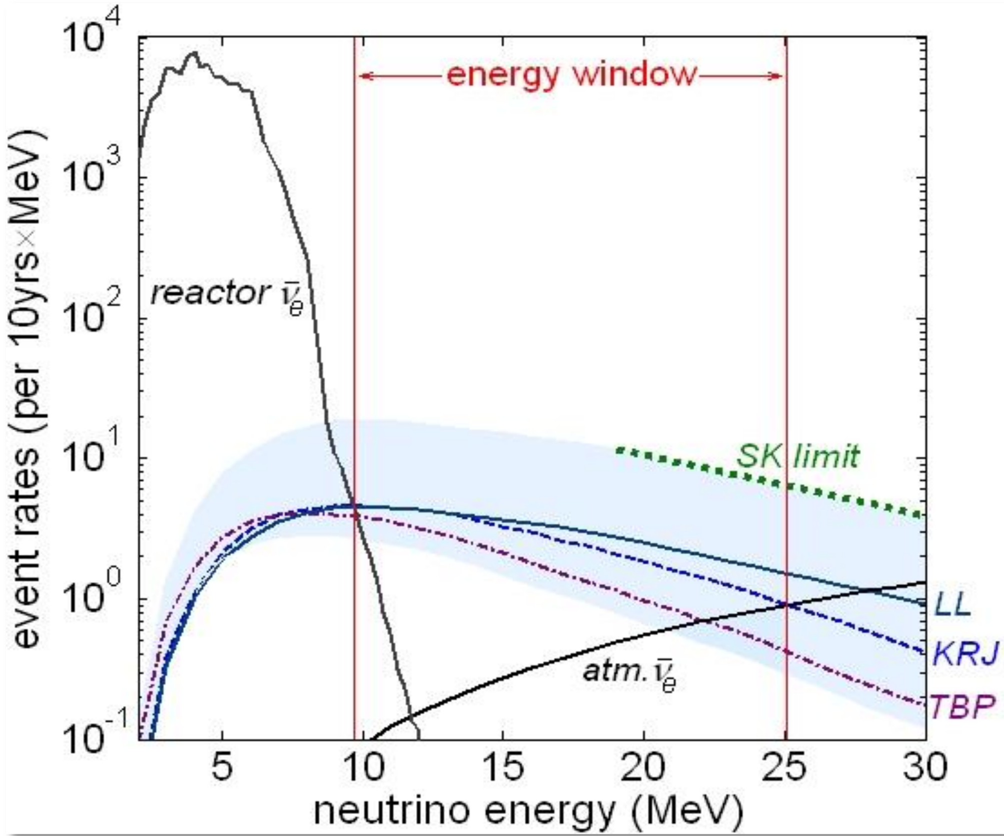
$$\overline{\nu}_e + p \rightarrow n + e^+$$

allows discrimination of most single-event background limiting the detection in SK

**Remaining Background Sources**

- reactor and atmospheric $\overline{\nu}_e$'s
- cosmogenic $\beta$n-emitters: $^9$Li
- fast neutrons
- **neutrons from atm. $\nu$'s (NC on $^{12}$C)**

**Expected rate: 5-20 ev/year in fid. vol.**
*(in energy window from 10-25MeV)*




**Scientific Gain**

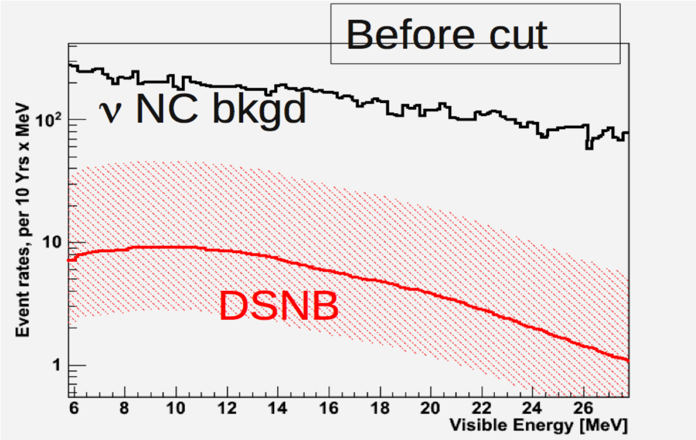
- first detection of DSN
- information on SN$\nu$ spectrum

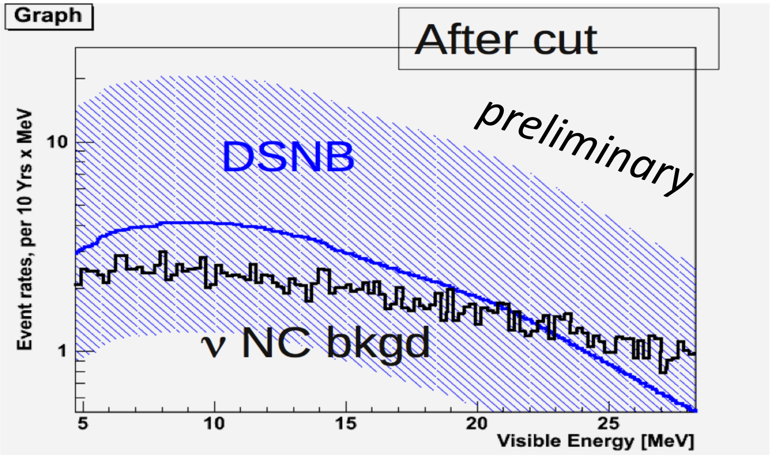
# DSNB background studies

- Cosmogenic produced neutrons
  - no problem if d > 4000 mwe
  - < 0.2 events / year
- Cosmogenic produced beta-neutron emitter (e.g. $^{9}$Li)
  - no problem if d > 4000 mwe
  - < 0.1 events / year
- Atmospheric neutrino CC reaction
  - 10 < E / MeV < 30
- Atmospheric neutrino NC reaction – neutron production
  - data from KamLAND
  - severe bg: reduction by pulse shape discrimination and statistical subtraction ?

*n-scattering TOF exp. at MLL*

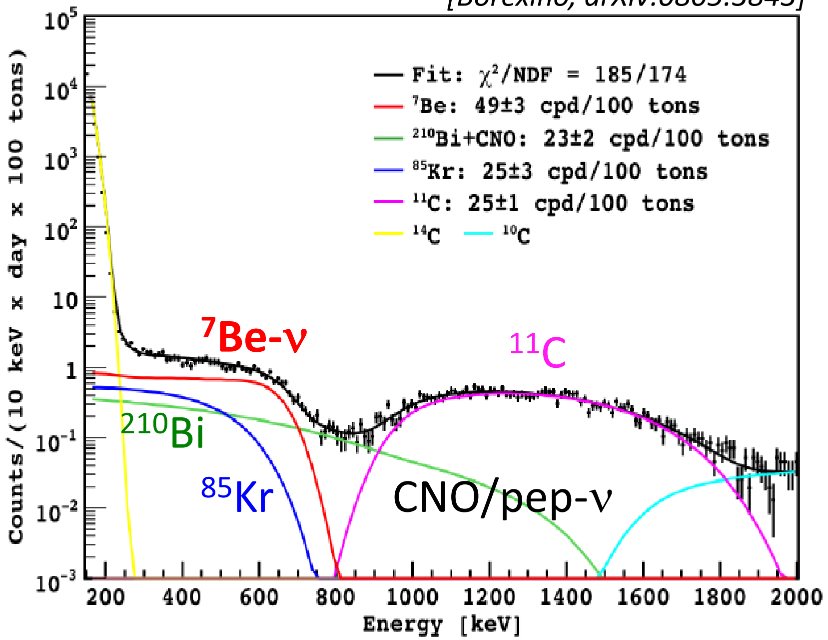
**Laboratory experiments indicate that a strong bg-reduction can be achieved**




***Preliminary** results: Monte-Carlo simulation based on recent results of PSD parameter on LAB scintillators*

# Solar Neutrinos in LENA




| Channel | Source | Neutrino Rate [$d^{-1}$] | |
|---|---|---|---|
| | | BPS08(GS) | BPS08(AGS) |
| $\nu e$ | pp | 24.92±0.15 | 25.21±0.13 |
| | pep | 365±4 | 375±4 |
| | hep | 0.16±0.02 | 0.17±0.03 |
| (18kt) | $^7$Be | 4984±297 | 4460±268 |
| | $^8$B | 82±9 | 65±7 |
| | CNO | 545±87 | 350±52 |
| $^{13}$C | $^8$B | 1.74±0.16 | 1.56±0.14 |

## Scientific Motivation

- determination of solar parameters (e.g. metallicity, contribution of CNO)
- search for temporal modulations in $^7$Be-ν (3σ discovery 0.5%)
- probe the MSW effect in the vacuum transition region → new osc. physics
- search for $\nu_e \rightarrow \nu_e$ conversion

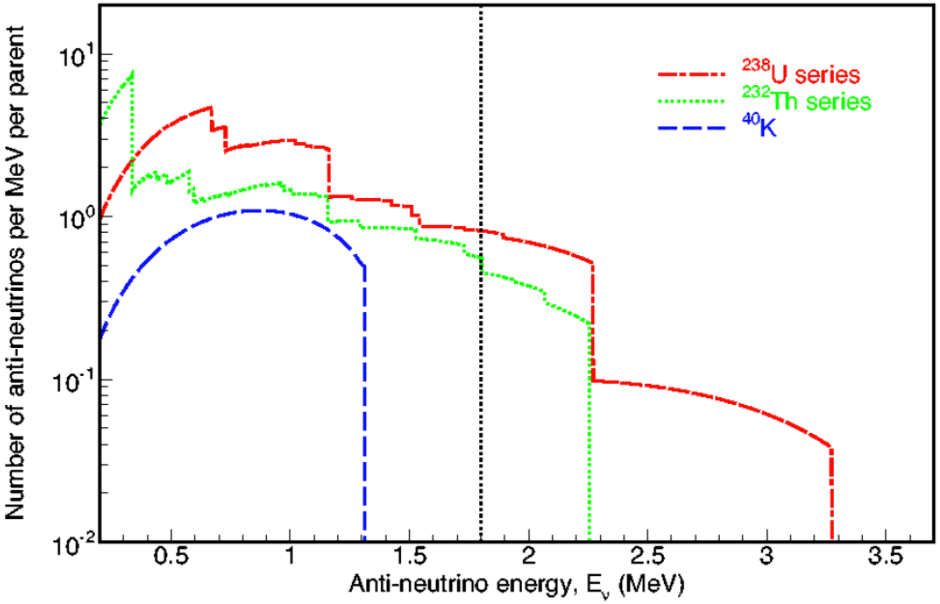
## Detection Channel

elastic νe scattering, E > 0.2MeV

## Background Requirements

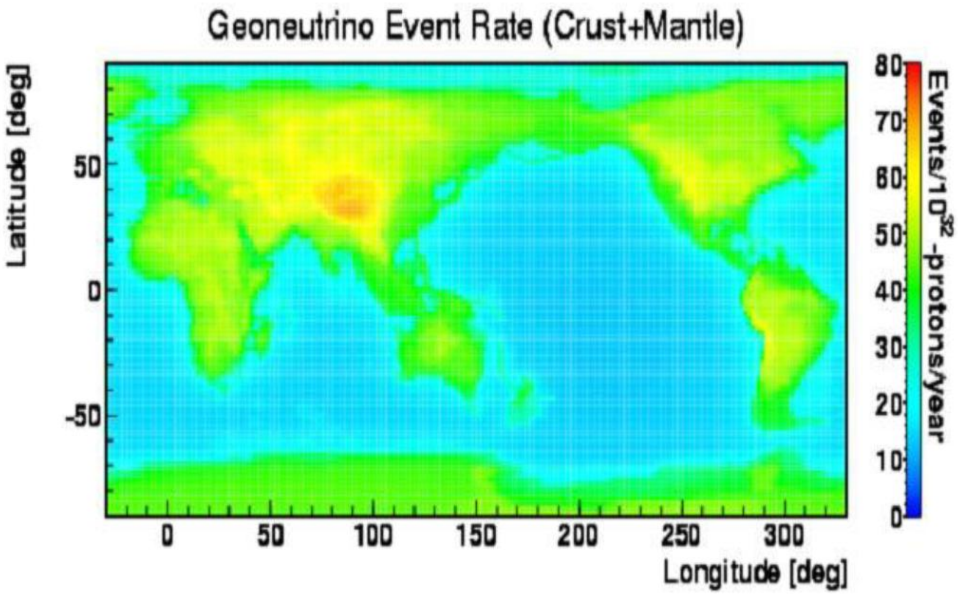
- U/Th concentration of $10^{-18}$ g/g (as achieved in Borexino)
- shielding of >3500 mwe for CNO/pep-ν measurement

# Geo neutrinos




Detect anti-neutrinos of the U, Th decay chains (inverse β-decay energy threshold is 1.8 MeV).

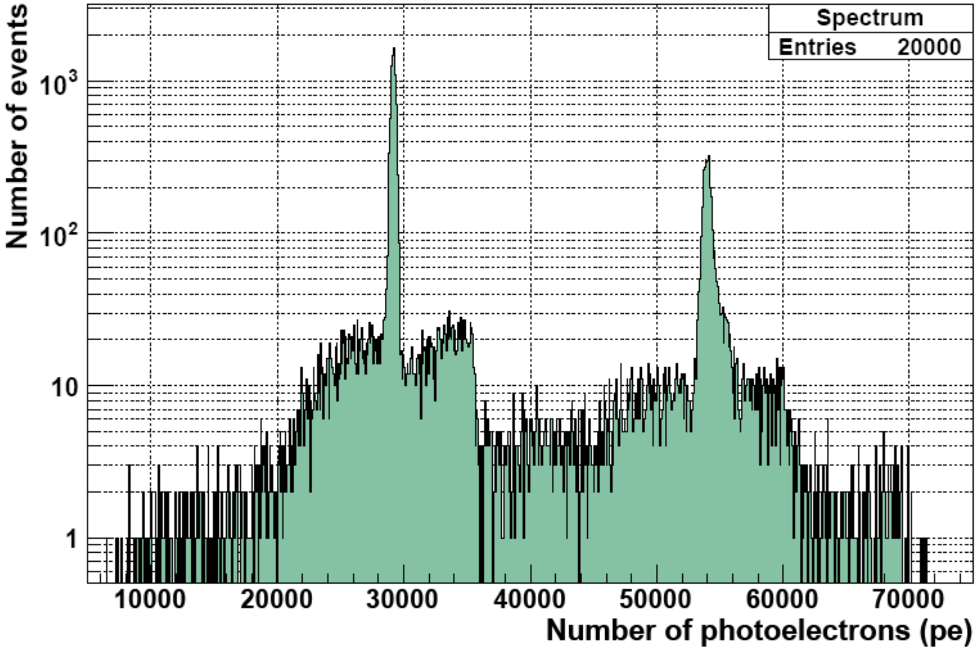
Expected event rate at Pyhäsalmi :
1500 events/year in 50 kt
Background from reactors:
700 events/year in 50 kt
in the relevant energy window




- ► measure flux from crust and mantle
- ► determine U/Th ratio
- ► disentangle continental/oceanic crust with more than one detector (HanoHano, EARTH)
- ► only detector within LAGUNA able to detect geo-neutrinos

# Sensitivity to proton decay **p → K⁺ν**

Simulated energy spectrum of 20000 proton decay events p → $K^+$v




High efficiency ($\varepsilon$=68%) and very good background discrimination ($10^{-4}$) by pulse shape discrimination
(main background: atmospheric neutrino interactions in the target)

Two peaks:

- Kaon + Muon ~ 257 MeV
- Kaon + Pions ~ 459 MeV

Energy-cut efficiency $\varepsilon_E$=99.5%, bound protons of $^{12}C$ included.

Potential of LENA (10y measuring time): **if no signal in LENA: $\tau > 4 \cdot 10^{34}$y (90% C.L.).**
background expectation for 10y: < 1 event.

Compare to current SuperKamiokande-IV limit: **$\tau > 4 \cdot 10^{33}$y (90% C.L.) with 220kt·y**

# LENA as long-baseline far detector


**Baseline**

- CERN to Pyhäsalmi: 2288 km
- 1$^{st}$ oscillation maximum 4 GeV
- Sensitive to mass hierarchy, CP violation, theta_13

Study this option (LAGUNA-LBNO)

Problematic bg: NC $\pi0$ production (decay into 2 gammas, resembles $\nu_e$ reaction)

**Under study:**
Event topology variables to seperate electrons from $\pi^0$ (e.g. asymmetry variable, rise time, mean time, tof-corrected first hit times, ...)

# Lepton flavour identification

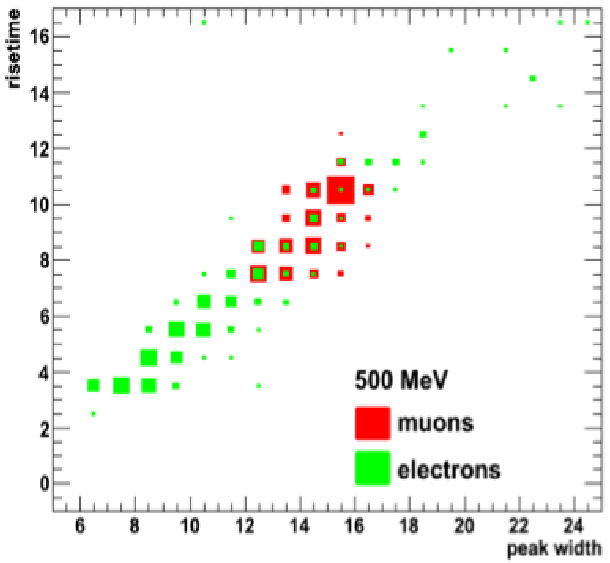
**For beta beams:**
$\nu_\mu$ appearance → $\nu_e$ rejection.

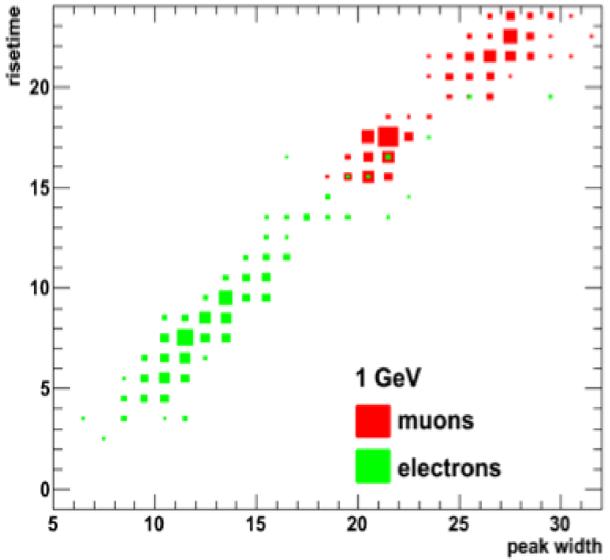
**i) Muon-decay electron:**

- muon has to decay sufficiently late
- energy threshold to reject spallation neutrons
- $\nu_e$ rejection efficiency: >99.95% (95%C.L.)
- $\nu_\mu$ acceptance: 85%

**ii) Pulse-shape discrimination:**

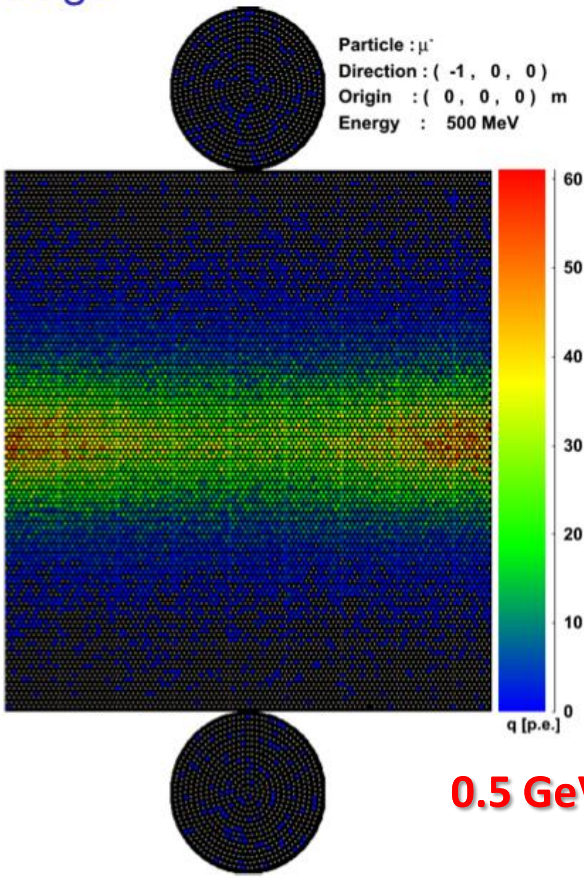
- rise time and peak width
- about 80% efficiency for $\nu_e$ rejection, but very powerful for $\nu_e$ selection
- discrimination of CC ($\nu_e$+$\pi^\pm$) interactions?



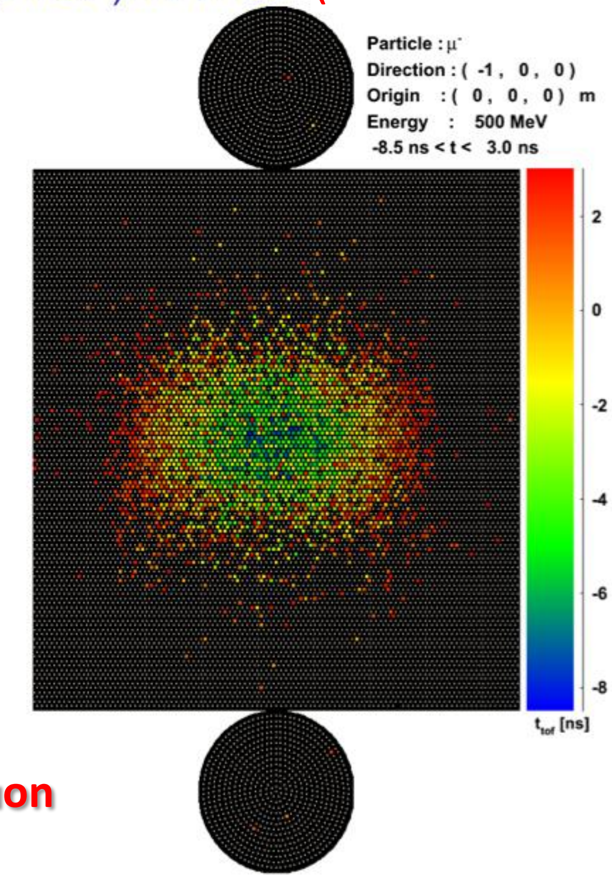



# Tracking in Liquid Scintillator

Charge




(First-)hit-time (TOF corrected)

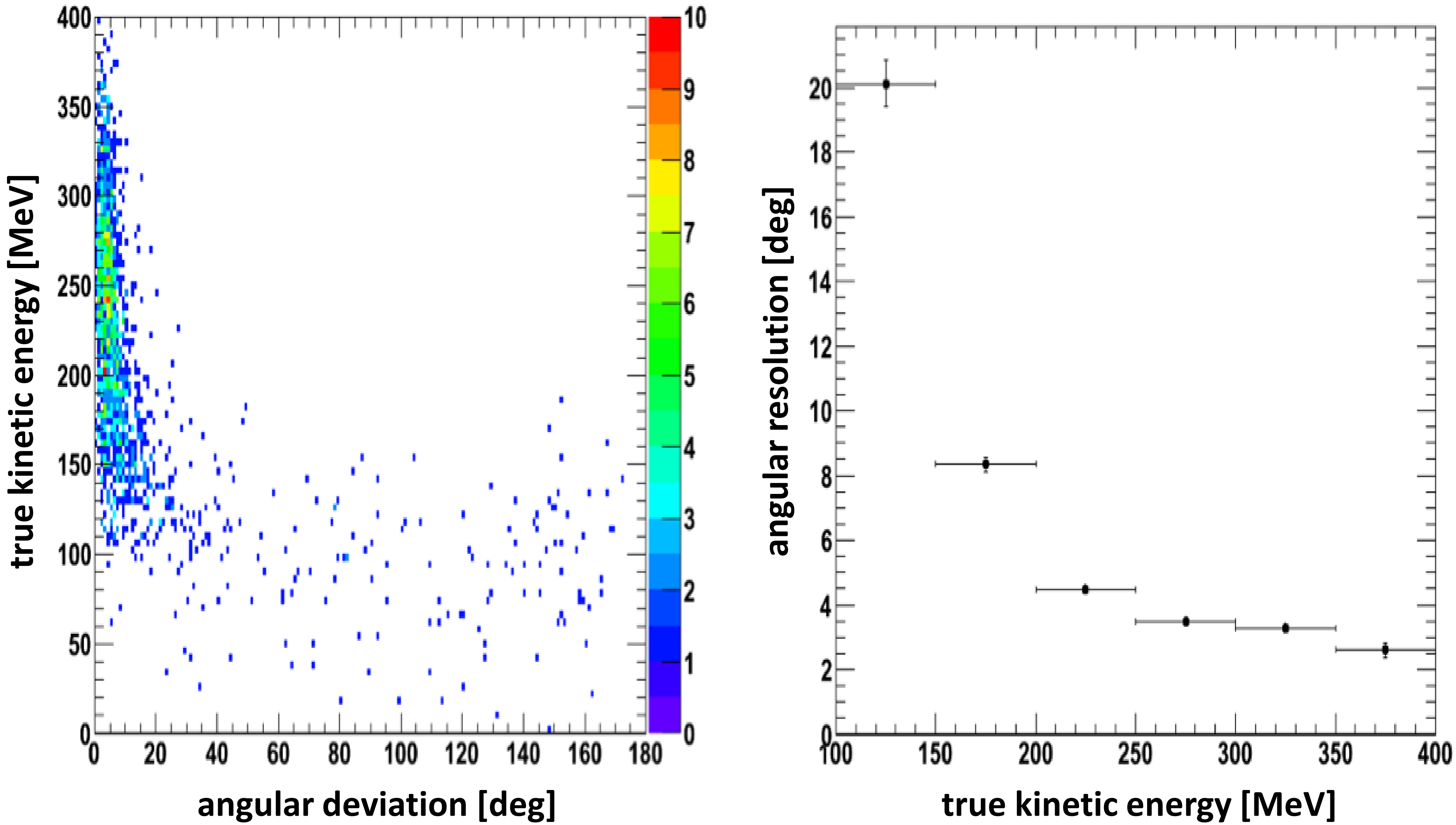



**0.5 GeV muon**

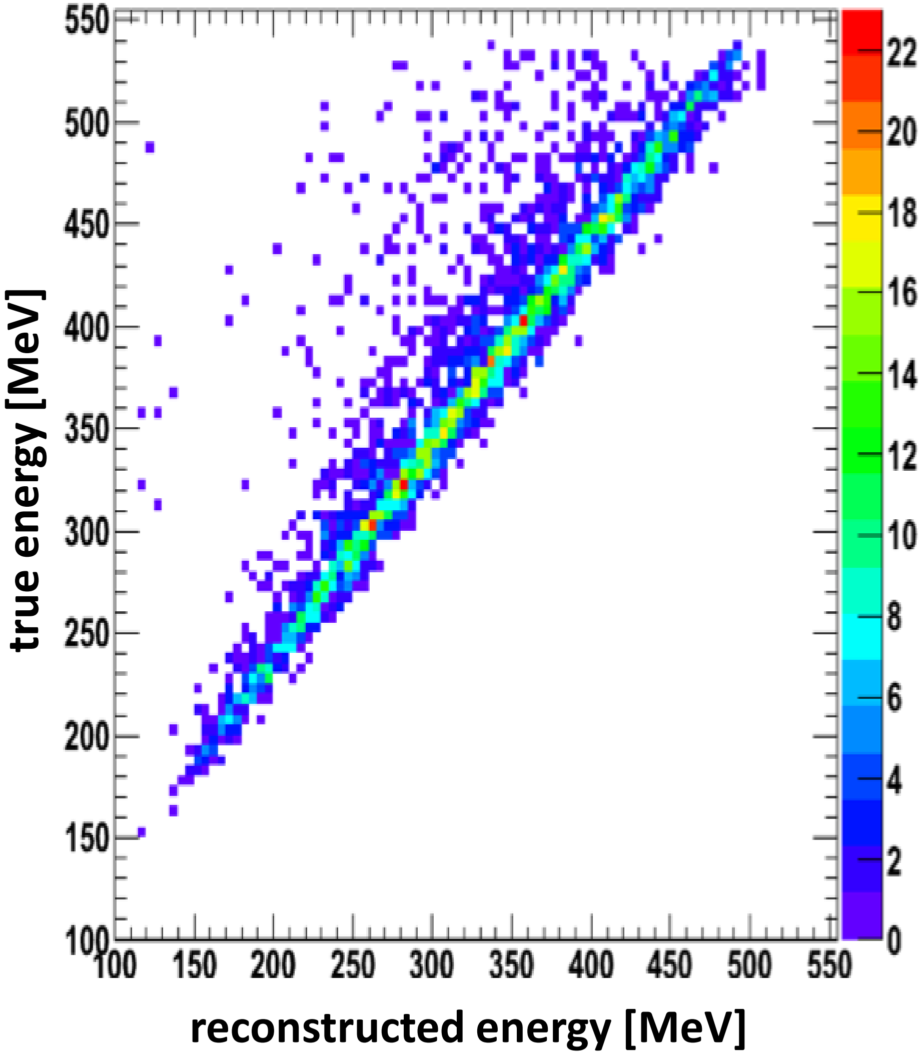
HE particles create spherical light fronts along their track that lead in superposition to a Cherenkov-like light cone.

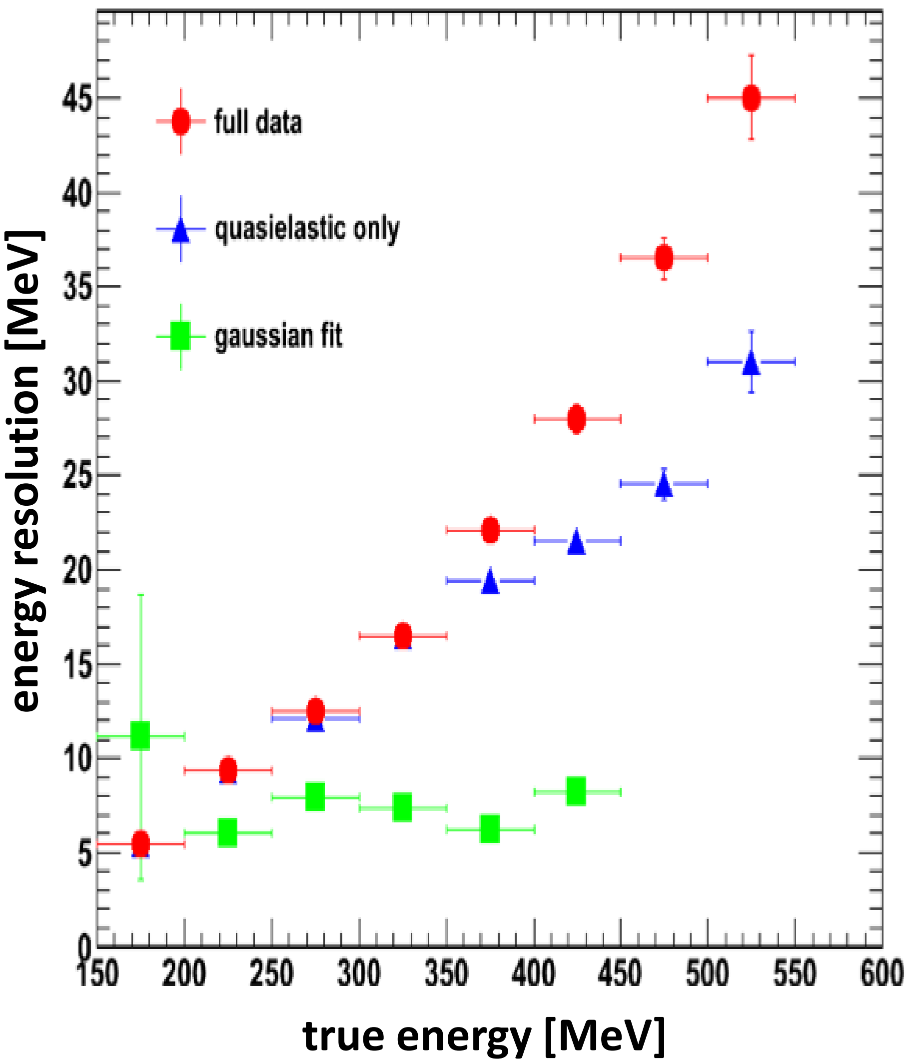
**But: about 50x more light!**

# Angular resolution, $\nu\mu$QE events



# Angular resolution, νμQE events



# LENA white paper

arXiv:1104.5620 (97 authors, 37 institutions)

**The next-generation liquid-scintillator neutrino observatory LENA**

Michael Wurm,[1,2,*] John F. Beacom,[3] Leonid B. Bezrukov,[4] Daniel Bick,[2] Johannes Blümer,[5] Sandhya Choubey,[6] Christian Ciemniak,[1] Davide D'Angelo,[7] Basudeb Dasgupta,[3] Amol Dighe,[8] Grigorij Domogatsky,[4] Steve Dye,[9] Sergey Eliseev,[10] Timo Enqvist,[11] Alexey Erykalov,[10] Franz von Feilitzsch,[1] Gianni Fiorentini,[12] Tobias Fischer,[13] Marianne Göger-Neff,[1] Peter Grabmayr,[14] Caren Hagner,[2] Dominikus Hellgartner,[1] Johannes Hissa,[11] Shunsaku Horiuchi,[3] Hans-Thomas Janka,[15] Claude Jaupart,[16] Josef Jochum,[14] Tuomo Kalliokoski,[17] Pasi Kuusiniemi,[11] Tobias Lachenmaier,[14] Ionel Lazanu,[18] John G. Learned,[19] Timo Lewke,[1] Paolo Lombardi,[7] Sebastian Lorenz,[2] Bayarto Lubsandorzhiev,[4,14] Livia Ludhova,[7] Kai Loo,[17] Jukka Maalampi,[17] Fabio Mantovani,[12] Michela Marafini,[20] Jelena Maricic,[21] Teresa Marrodán Undagoitia,[22] William F. McDonough,[23] Lino Miramonti,[7] Alessandro Mirizzi,[24] Quirin Meindl,[1] Olga Mena,[25] Randolph Möllenberg,[1] Rolf Nahnhauer,[26] Dmitry Nesterenko,[10] Yuri N. Novikov,[10] Guido Nuijten,[27] Lothar Oberauer,[1] Sandip Pakvasa,[28] Sergio Palomares-Ruiz,[29] Marco Pallavicini,[30] Silvia Pascoli,[31] Thomas Patzak,[20] Juha Peltoniemi,[32] Walter Potzel,[1] Tomi Räihä,[11] Georg G. Raffelt,[33] Gioacchino Ranucci,[7] Soebur Razzaque,[34] Kari Rummukainen,[35] Juho Sarkamo,[11] Valerij Sinev,[4] Christian Spiering,[26] Achim Stahl,[36] Felicitas Thorne,[1] Marc Tippmann,[1] Alessandra Tonazzo,[20] Wladyslaw H. Trzaska,[17] John D. Vergados,[37] Christopher Wiebusch,[36] and Jürgen Winter[1]

# Backup slides

# What waits at the 50-kt scale?

*1) Precision measurements of known neutrino sources*

Sun, Earth's interior,
Supernovae
nuclear reactors, EC sources

*2) Search for very faint signals*

Diffuse SN neutrinos,
Dark Matter annihilation

*3) Access to the GeV energy region*

Long-baseline neutrino beams,
atmospherics, proton decay

# Europe: LAGUNA

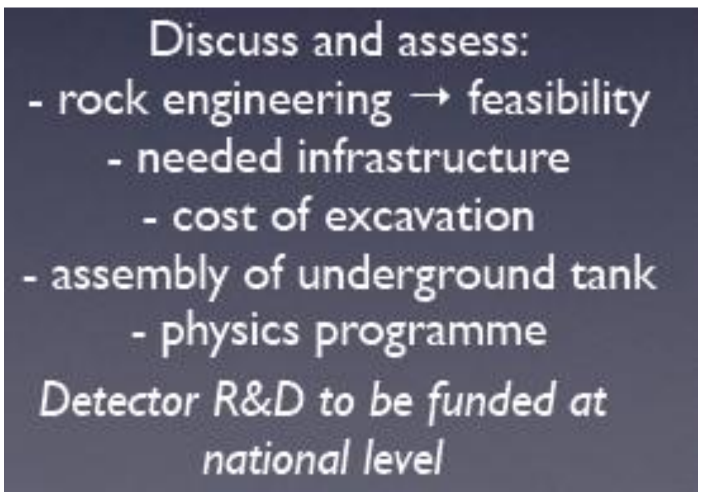
Consortium composed of 21 beneficiaries in 9 countries

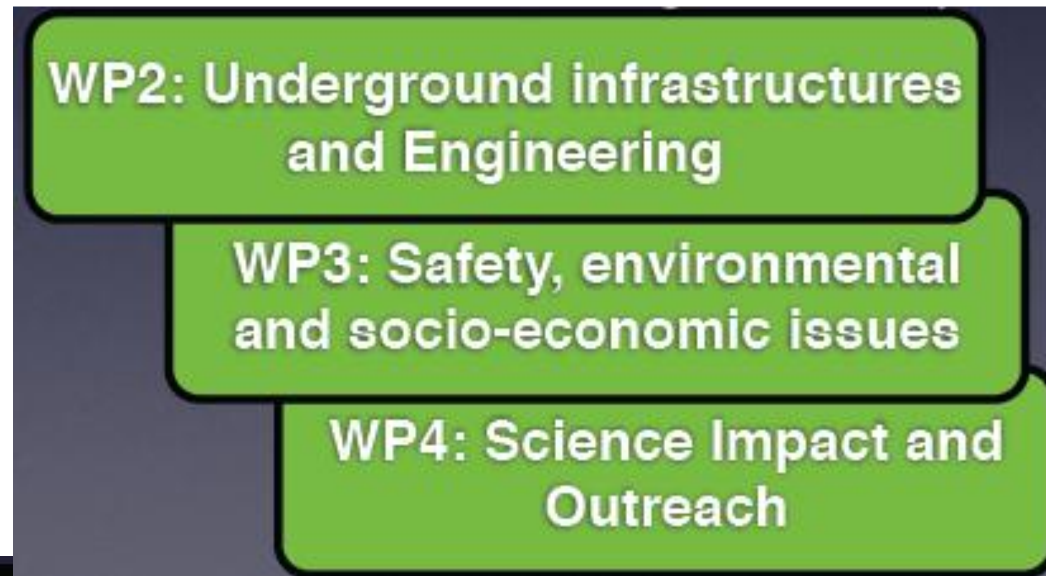
9 university entities (ETHZ, Bern, Jyväskylä, OULU, TUM, UAM, UDUR, USFD, UA)

8 research organizations (CEA, IN2P3, MPG, IPJ PAN, KGHM CUPRUM, GSMiE PAN, LSC, IFIN-HH)

4 private companies (Rockplan, Technodyne, AGT, Lombardi)

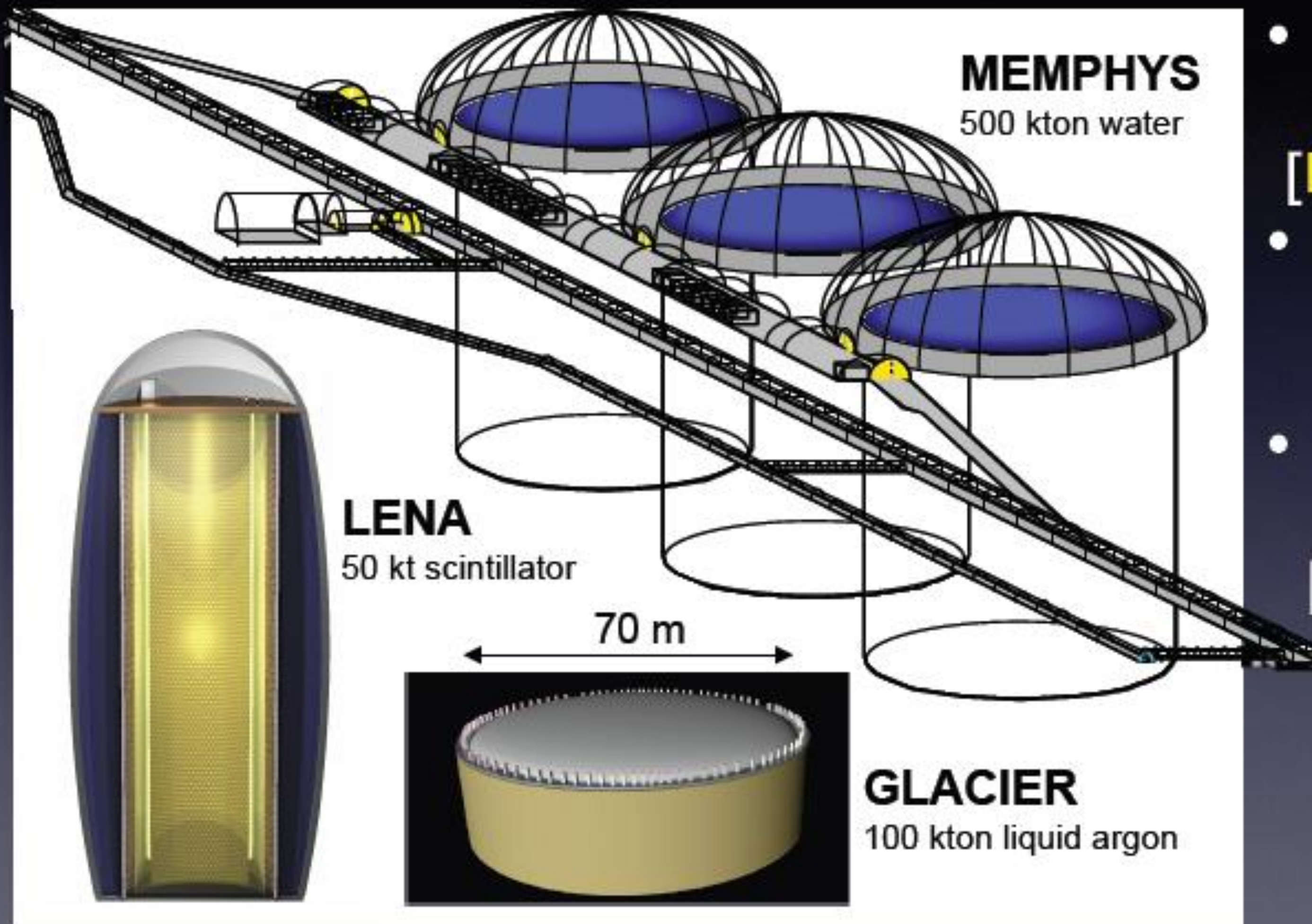
Additional university participants (IPJ Warsaw, Silesia, Wroclaw, Granada)




# Europe: LAGUNA

- three options considered (MEMPHYS, LENA, GLACIER) with total mass in the range 50-500 kton




- Water Cerenkov **[MEMPHYS]**
- Liquid scintillator **[LENA]**
- Liquid Argon TPC **[GLACIER]**

# Europe: LAGUNA